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Dredging Research Technical Notes

The Viscous Characteristics of Channel-Bottom Muds

Purpose

The purpose of this note is to establish a background that can be used for subsequent Dredging Research Program (DRP) development of criteria for defining the limiting depth for safe navigation in areas of fluid mud and as rational means of characterizing fluid mud deposits that affect navigation. Establishing a navigable depth criterion will require evaluation of mud characteristics and terminology not widely applied within the U.S. Army Corps of Engineers. A subsequent technical note will use viscosity as a key element in the analysis of frictional effects on vessels operating with no underkeel clearance in fluid mud areas.

Background

The Corps of Engineers has the mission to maintain Federal navigation projects. Much of the sediment materials dredged from waterways are fine-grained, cohesive muds, some with densities ranging from 1.05 to 1.25 g/cu cm. Unlike sands, fine-grained fluid muds are slow to consolidate and can persist in a fluid-like state for long periods. Thick layers of fluid mud occur at some times and at some places, especially in estuaries where fine sediments are often trapped. If the density and viscosity of a particular mud are sufficiently low, it is navigable; however, the margin between navigable and nonnavigable fluid mud conditions is ill-defined, leading to either unsafe navigation, inefficient dredging, or both.

The material property which produces greatest frictional effect is viscosity. Although density and viscosity are related, that relationship can be complicated by other factors. However, of the parameters most directly related to navigability, only density can be measured in situ.

Technical developments are being made by the DRP which will enable rapid survey of depth and density in muddy navigation channels. Direct measurements of density will provide more complete, less ambiguous information on channel conditions than present conventional acoustic surveys.

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Depth and density, combined with other site information, will allow the definition of the elevation of the navigable bed: an operational definition of the channel bottom. This information could reduce maintenance dredging costs by:

- Identifying that sediment which actually impedes navigation.
- Improving dredging priorities by better identifying shoaling hazards.
- Providing the means for more accurate scheduling of dredging operations.
- Better describing sediment material removed by dredging operations.

Additional Information

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Scope

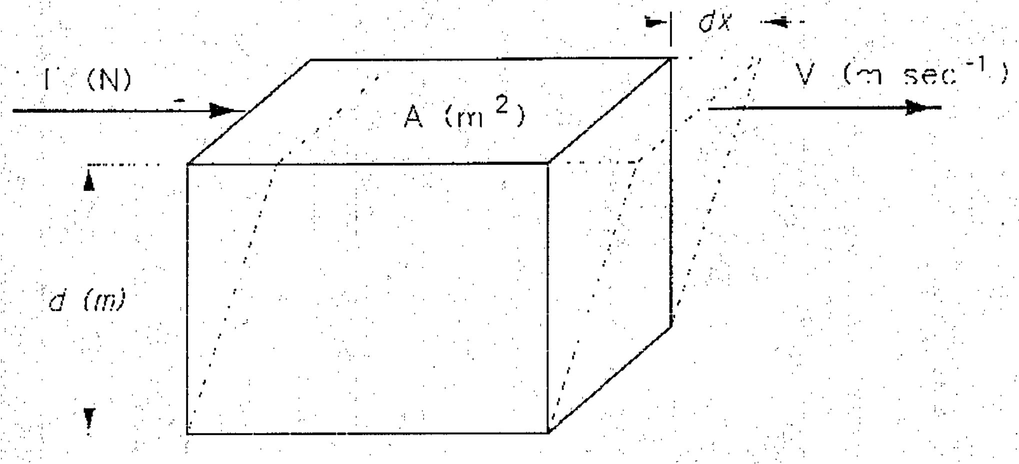
What follows includes an introduction to the stress-strain relationships for fluids and ideal suspensions, leading to a description of observed viscosity relationships for the complex natural suspensions termed fluid muds. It will be shown that fluid mud characteristics interact with vessels in two general ways. One involves relatively large forces to break loose, and the other involves relatively lower forces while underway. These characteristics are important considerations in defining what fluid mud is navigable.

Viscosity of Water

The viscosity of a material is its resistance to change in form, expressed in SI (metric) units of pascal-seconds (Pa-sec) or units of poise (dyne-seconds per square centimeter). Pure water has a viscosity (η) of about 0.001 Pa-sec which is related to its molecular properties and varies only slightly with temperature and dissolved solids. The stress-strain relationship for laminar flow can be expressed as:

$$\tau = \eta \dot{\gamma}$$

where τ is the shear stress in pascals (N per sq m), and $\dot{\gamma}$ is the shear rate of the fluid. This is the Newtonian model for flows — stress proportional to strain — when η is considered to be a constant. Though they might be almost entirely water, suspensions have different stress-strain relationships. Figure 1 shows definitions for terms related to fluid deformation.



SHEAR STRESS $\tau = F/A$ (N/sq m or Pa)

SHEAR RATE $\dot{\gamma} = V/d$ (sec^{-1})

VISCOSITY $\eta = \tau/\dot{\gamma}$ (Pa sec)

Figure 1. Definition of terms used to describe the deformation of a fluid block

Viscosity of Ideal Suspensions

A suspension of rigid spheres has an effective viscosity η^* which is made up of the suspending fluid viscosity, and an additional component related to the solids. The concentration of solids has an important effect on η^*. Albert Einstein was the first to seriously consider the effective viscosity of a suspension, and he developed the following theoretical relationship between η^* and solids content:

$$\eta^* = \eta\ (1 + 5/2\ \phi)$$

where ϕ is the volume concentration of the solids. While this relationship has been verified for ideal particles, fluid mud η^* is more complex and also depends on flow properties, particle size distribution, particle shape, ionic content of the suspending fluid, and organic content (Jeffrey and Acrivos 1976).

Fluid Mud

Fluid mud does not have a precise definition, but is generally considered to be a cohesive fine-grained sediment suspension with a concentration below that required for the formation of important soil structure. Fine-grained sediments are less than 74 μm (pass the No. 200 sieve), and, more importantly, include those which exhibit cohesion. Cohesion is very important to viscosity, as will be discussed later. Fluid mud generally refers to suspension concentrations ranging from about 50 to 350 dry-g/L, corresponding to a bulk wet density range from about 1.05 to 1.25 wet-g/cu cm or to ϕ of 0.02 to 0.13 cu cm solids/cu cm mud.

In some cases fluid mud can move with the flow, or it can remain stationary and gradually consolidate by settling and self-weight into a heavy sediment. Fluid muds generally form a lutocline, an area of steep vertical density gradient near the bed. Figure 2 shows a typical fluid mud vertical structure.

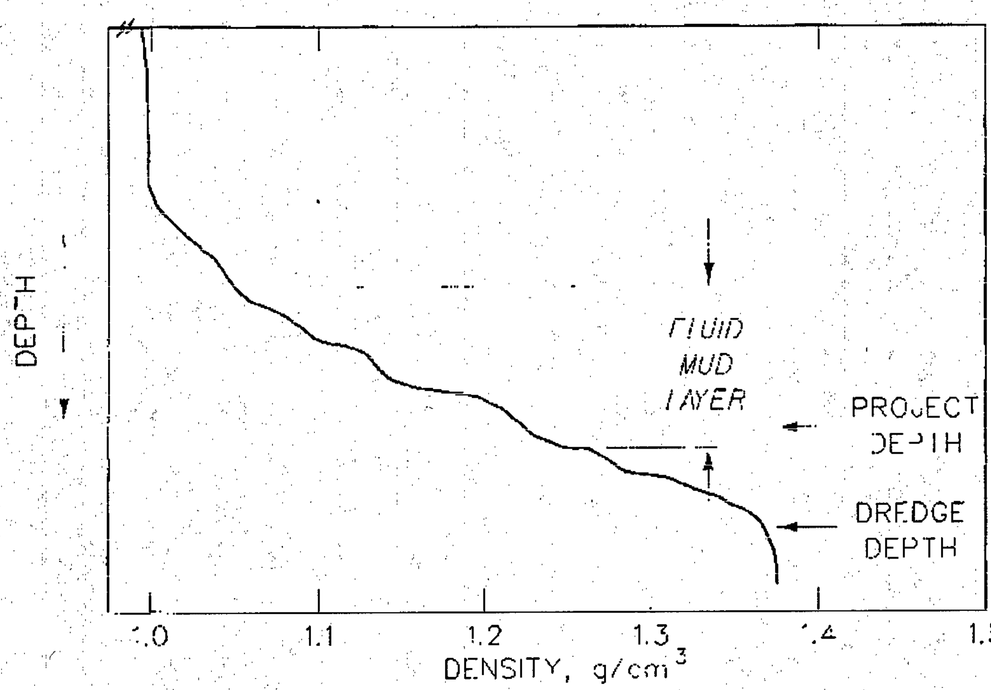


Figure 2. Schematic vertical structure of fluid mud in a navigation project

Models of Fluid Mud Viscosity

Cohesive suspensions such as fluid muds have viscosities which depend quite strongly on $\dot{\gamma}$, and are thus termed non-Newtonian. Non-Newtonian behavior can be a nonlinear stress-strain relationship, or a yield stress below which a stress produces no deformation (strain). Cohesion between particles creates flow units of varying size and shear strength, and is

responsible for the non-Newtonian behavior of fluid mud suspension (Krieger and Dougherty 1959).

Many models have been applied to describe the viscometric behavior of fluid muds. Several simple models can express the relationship (Herbich and others 1989).

- Power Law Model:

$$\eta^* = m\ \dot{\gamma}^{n-1}$$

where m is the consistency (viscosity at $\dot{\gamma} = 1$ per sec) and n is the flow index (a measure of the non-Newtonian character of the fluid).

- Bingham Plastic:

$$\eta^* = \tau_b\ \dot{\gamma}^{-1} + \eta_h$$

where τ_b is the Bingham yield stress in our case defined over an appropriate time scale, and η_h is the high-shear limiting viscosity. The important roles τ_b and η_h play in forces on vessels will be discussed later.

- Carreau Model:

$$\eta^* = \eta_h + \frac{\eta_o - \eta_h}{1 + (K\dot{\gamma})^2)^b}$$

where η_o is the low-shear Newtonian viscosity, K is a characteristic time constant, and b = (1 - n)/2. The parameters in these models, with the exception of b, are dependent on solids content, particle characteristics, and fluid chemistry, and are therefore highly variable. This model simplifies to other models in special cases. Note in particular that when $\eta_o >> \eta^* >> \eta_h$ and b = 1/2, it reduces to the Bingham Plastic model where:

$$\tau_b = \eta_o\ K^{-1}$$

Discussion of Fluid Mud Models

Of the three models described earlier, the Carreau model was found to best represent experimental data in a recent study of channel muds (Herbich and others 1989). Figure 3 shows an example of η_o and η_h

for a sediment plotted against concentration and shows the relative magnitude between η_o and η_h. The parameter b was taken to be a constant with a value of about 0.5, and thus the Carreau model was equivalent to the Bingham Plastic model for the sediments tested.

The Carreau model tells us that fluid mud has Newtonian plateaus at low and high shear rates (Figure 4). However, instrument limitations in that study prevented the high shear plateau from being measured directly, and extrapolations were made from lower $\dot{\gamma}$ values. Muds from several sites were tested, and results varied between sites and between samples from the same site.

Since for fluid muds generally $n < 1$ and suspensions become thinner or less viscous as $\dot{\gamma}$ increases (shear thinning), the frictional effect of fluid mud η^* on a moving vessel is nonlinear. Shearing in fluid mud flows becomes confined and intensified, relative to clear water, in the boundary layer next to the hull, and this partially compensates for low-shear viscosities. Viscosities near the high shear limit might become most important in the case of a moving vessel, as will be described in a subsequent technical note.

As described earlier, fluid muds generally have yield stresses or related low-shear viscosities. Measuring the yield stress either directly or indirectly (by extrapolating from low shears) has been difficult to do with certainty (James, Williams, and Williams 1987). Because test results

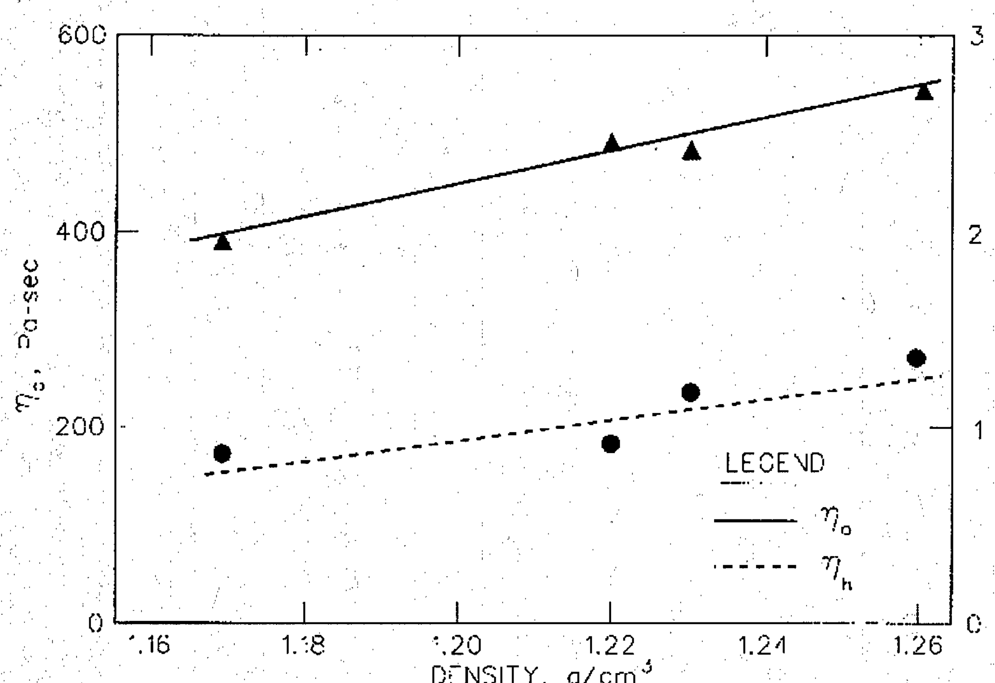


Figure 3. Example η_o and η_h dependence on density for Canaveral Barge Canal, Florida, mud (from Herbich and others 1989)

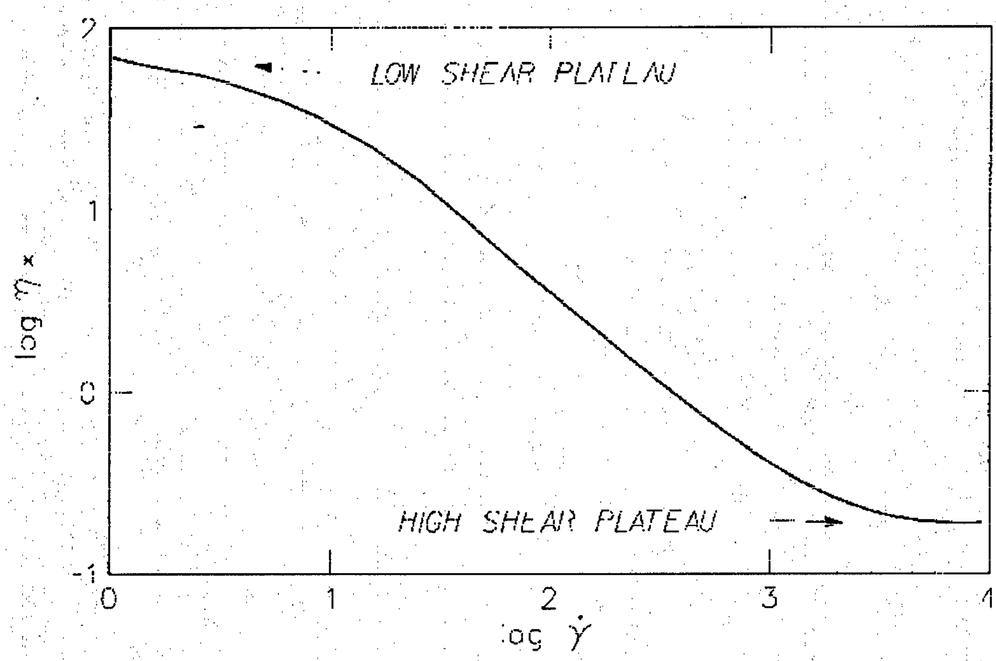


Figure 4. Schematic $\eta* - \dot{\gamma}$ curve showing low and high shear plateaus

depend on measurement procedures, and because a finite stress eventually results in a finite strain (implying a zero yield stress), the yield stress has taken on a mythical quality (Barnes and Walters 1985). Yield stress must be defined with respect to some appropriate time scale. Recent advances in measurement techniques make it possible to estimate yield stresses with more certainty.

Studies have often concentrated on yield stress τ_b or initial rigidity to characterize fluid mud with respect to navigation (Granboulan and others 1989), to dredgeability (Cox, vanDeurson, and Verhoeven 1986), or to hydraulic shear strength (Krone 1963, and Otsubo and Muraoka 1988). Vessels starting from rest in fluid mud must overcome the yield stress for that mud over the entire area of contact. Vessels moving through fluid mud must overcome the yield stress at their bow sections to initiate shear in the mud.

Normal Stresses

Other forces are produced where fluid mud is capable of transmitting normal forces through a space-filling structure. This occurs at higher relative concentrations beginning at about ϕ = 0.06, 1.12 wet-g/cu cm, or 150 dry-g/L. Customarily, the complete viscometric function is expressed as three scalars: the shear viscosity ($\eta*$) and two normal stress quantities with pressure eliminated. Simplifying somewhat, total stress (τ_t) can be expressed as a tangential or viscous (τ) component and a single normal (τ_y) component:

$$\tau_t = \tau + \tau_y$$

A relationship for the normal stress component developed for bentonite clay (Wright and Krone 1987) was:

$$\tau_y = a - b \ln \dot{\gamma}$$

where the empirical coefficients, a and b, were found to depend on the concentration of the fluid mud. Thus, the normal stress component was found to be partly dependent on $\dot{\gamma}$, the rate of shear, in the negative sense.

Summary and Applicability

The effective viscosity of fluid mud material affects the boundary layer stresses around the hull of a vessel moving through it, and is thus an important factor in the meaningful definition of navigable depth in muddy areas.

Effective flow properties of muds depend on interaggregate spaces, and hence on the concentration or density of the material and its flocculation state. Factors such as cohesion, particle size distribution, organic content, and pore water chemistry affect the behavior of fluid mud. Therefore, fluid muds from different locations can act differently, even at the same concentration or density.

Basic descriptors which have been discussed and will be useful in the process of establishing navigable depth criteria include:

- **Yield stress** - the apparent stress required to initiate mud motion.
- **Low-shear viscosity** - the effective viscosity of muds at or below about $\dot{\gamma} = 1\ \text{sec}^{-1}$.
- **High-shear viscosity** - the effective viscosity of muds at $\dot{\gamma} = 300\ \text{sec}^{-1}$ or greater.

However, the actual navigable depth criteria will be based on other field-measureable parameter(s) such as density.

Fluid muds are non-Newtonian fluids whose flow properties depend strongly on their rate of shear. They are generally *shear thinning*, but have a lower-limit viscosity at high shear rates. Fluid muds may have a finite yield stress which could affect vessels just getting underway differently from those moving.

Effective normal stresses occur in fully settled mud, or in the concentration range where fluid mud is in transition to a sediment. These

normal forces are responsible for vessel grounding in granular material such as sand. However, similar forces can develop at relatively low concentrations due to the ability of cohesive sediments to form continuous space-filling structure at volume concentrations only on the order of 0.06.

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